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Stoneley Wave Predicted Permeability and Electrofacies Correlation in the Bangestan Reservoir, Mansouri Oilfield, SW Iran

Bahman Soleimani*, Mehrdad Moradi and Ali Ghabeishavi

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Resumen

La caracterización de los yacimientos es una de las metas más importantes para la explotación de los campos petroleros. Determinar la permeabilidad y el tipo de rocas es de primordial importancia para conocer la calidad del yacimiento. En este trabajo se utilizan las ondas de Stoneley a partir de herramientas sónicas bipolares para encontrar cambios de permeabilidad en el yacimiento Bangestan, del campo petrolero Mansouri. Se estimó el índice (tortuosidad) con ondas Stoneley. Después de comparar la permeabilidad resultante de las ondas de Stoneley, núcleos y el método Timur, se concluye que las tres permeabilidades son muy parecidas. La porosidad de los núcleos y la porosidad efectiva obtenida del análisis de muestras de pozos fueron similares. El método de electrofacies (EF), como método de comparación, se utilizó para encontrar tipos de rocas que definieran las zonas internas y externas al yacimiento. Simultáneamente con la compactación EF, se consideraron e interpretaron datos de radiación gamma, porosidad neutrónica, densidad, sonar, saturación de agua y porosidad de 78 pozos. Como resultado del análisis se definieron 9 cúmulos, que después de considerar datos de presión capilar (CP) se redujeron a 4. Los cúmulos 1 y 2 presentan mayor porosidad. En EF 3 se observó mayor abundancia de fracturas y solutos comparado con las otras EFs. Basado en un tipo matricial se encontró la clasificación de porosidad Archie de tipos I y III. El tamaño del poro en EF 1 y 2 fue esencialmente del tipo B mientras que EF 3 fue del tipo A. Las EFs generadas y determinadas con ondas Stoneley y registros de datos de los pozos también se compararon presentando buena correlación.

Palabras clave: Ondas Stoneley, herramientas sónicas bipolares, yacimiento Bangestan, campo petrolero Mansouri, electrofacies.

Abstract

Reservoir characterization is one of the most important goals for the development of any oilfield. Determination of permeability and rock types are of prime importance to judge reservoir quality. In this research, Stoneley waves from dipole sonic tools were used in order to discover changes in permeability in the Bangestan reservoir, Mansouri oilfield.

Index (tortuosity) could be estimated by Stoneley waves. After comparing the permeability resulting from Stoneley waves, cores and the Timur method, it was concluded that all the three permeabilities were very similar. The core porosity and effective porosity from the analysis of well logs were found to match as well. Electrofacies (EF) method, as a clustering method, was utilized to find rock types in order to define reservoir and non-reservoir zones. Simultaneous with EF clustering, gamma ray, neutron porosity, density, sonic, water saturation and porosity (PHIE) data from 78 wells were also considered and interpreted. Nine clusters were defined as a result of the analysis, being reduced to only four clusters after applying PC (capillary pressure) data. Among the four clusters, clusters 1 and 2 contained more vuggy pores than the others. Fracture abundance and solution seams were observed more frequently in EF-3 as compared to other EFs. Based on the matrix type, Archie porosity classification types I and III were recognized. The pore sizes in EFs-1 and 2 were mostly of the B type while in EF-3, it was A type.

The EFs generated and determined by Stoneley waves and the well log data were also compared, showing a good correlation.

Key words: Stoneley wave, Dipole sonic tools, Bangestan reservoir, Mansouri oilfield, Electrofacies.

M. Moradi
Geology Dept.
Shahid Chamran University of Ahvaz
Ahvaz, Iran.
Second add: National Iranian Drilling Company
Well Logging Operation
Ahvaz, Iran.

A. Ghabeishavi
Dept. of Developing Geology
National Iranian Oil Company
Ahvaz, Iran.

B. Soleimani*
Geology Dept.
Shahid Chamran University of Ahvaz,
Ahvaz, Iran.
*Corresponding author: soleimani_b@scu.ac.ir

Introduction

Understanding the characteristics of any reservoir is of prime importance to the development of any oilfield. Accordingly, hydrocarbon interval and prediction of hydrocarbon production in each drilled well are vital for petrophysical study and their evaluation and also to pinpoint a new well in future drilling project.

The petrophysics study is extremely important to find out some key parameters such as reservoir permeability. Permeability and porosity are dependent upon the texture and rock fabric. Widespread changes in all types of porosity and variation in pore throat from the micron scale (up to 350 μm) to the nano-scale (below to 1-3 nm) (Eigmati *et al.*, 2011; Josh *et al.*, 2012; Ortega and Aguilera, 2014) are effective in quantifying the permeability (Gao and Hu, 2013). Pore throat variation is more effective in computing permeability as compared to the size of the pore itself. Moreover, pore throat can be reckoned by the size of the pore. The pore throat size and its distribution are important in many fluid transport processes (Lake, 1989; Anovitz and Cole, 2015), the fluid saturation distribution, porosity, permeability, and to some extent, wettability (Green, 2009) and seismic properties (Batzle and Wang, 1992; Malembo, 2015) or the properties of the entire rock mass as well (Collet and Gurevich, 2013) in reservoir rock.

There are several methods to estimate permeability (Anissofira, and Latief, 2015; Brown, 2015; Gupta and Maloney, 2015; Luijendijk, and Gleeson, 2015; Sadeq *et al.*, 2015; Wang *et al.*, 2016; Wei *et al.*, 2015). Reservoir analysis and evaluation is dependent upon the characteristics of reservoir geology as well as the indication of the formation porosity and pore throat. The aim is to infer the petrophysical properties of the reservoir rock, gain awareness about parameters, and finalize the spatial map extent of the flow unit. Due to lack of adequate information from the reservoir, we are obliged to employ different methods to find the permeability. If permeability is found by any specific technique, almost all the parameters of the reservoir can be correlated and determined. Separation of rock types by different procedures is also useful to study the reservoir quality and sometimes the reservoir zoning of certain reservoirs. A full description of the reservoir requires a perfect combination of geological and petrophysical data so that the researchers can determine the characteristics

of the reservoir as close as possible to the real geology (Abbaszadeh *et al.*, 1996; Amaefule *et al.*, 1993; Rebelle *et al.*, 2009; Tiab and Donaldson, 2004).

Determining all rock types in a reservoir and the variation in characteristics in horizontal and vertical directions constitute one of the most important analyses in the process of characterizing a reservoir (Bagheri and Biranvand, 2006; Lucia, 2007; Serra, 1986; Serra and Abbott, 1982; Serra and Sulpice, 1975). To determine the rock type, it is necessary to use specific materials including the study of well logs with high resolution and the dynamic data in that specific direction. A simplified connection must also be created between the petrophysical data and the facies statistics (Rebelle *et al.*, 2009). In definition, the rock type is a facies collection with distinguished criteria incorporated in one group (Schlumberger, 1989; Rabiller, 2005; Ye and Rabiller, 2000, 2005). In this paper, efforts have been made to utilize Stoneley waves in the Mansouri oilfield in Bangestan reservoir to estimate permeability data with high accuracy from Stoneley waves as electrofacies detection. This method has been applied by other researchers (Uspenskaya *et al.*, 2012).

Mansouri oilfield position

Mansouri oilfield is located in Khuzestan province, southwest of Iran. Without any outcrop, this field has been defined by surface seismicity. The trend in the structure of this field is similar to the adjacent fields such as the Ahwaz, Maroun and Shadegan oilfields, following the Zagros trend (Fig. 1).

The oil field understudy consisted of different reservoirs such as Asmari, Bangestan and Khami. The Bangestan reservoir (Cretaceous age), divided into two parts: the Ilam (limestone and shale, Santonian-Campanian), and Sarvak (limestone, Cenomanian-Turonian) formations as the upper and lower reservoirs respectively. These reservoirs are separated due to the Lafan shale at the base of Ilam Formation. According to geophysical survey maps, the Mansouri structure is 43 km in length and 6 km wide from the top of Ilam Formation.

Methods

In the present paper, Stoneley wave and electrofacies were used to evaluate the reservoir quality and to give a comparison between all estimated permeability data and electrofacies in the Bangestan reservoir.

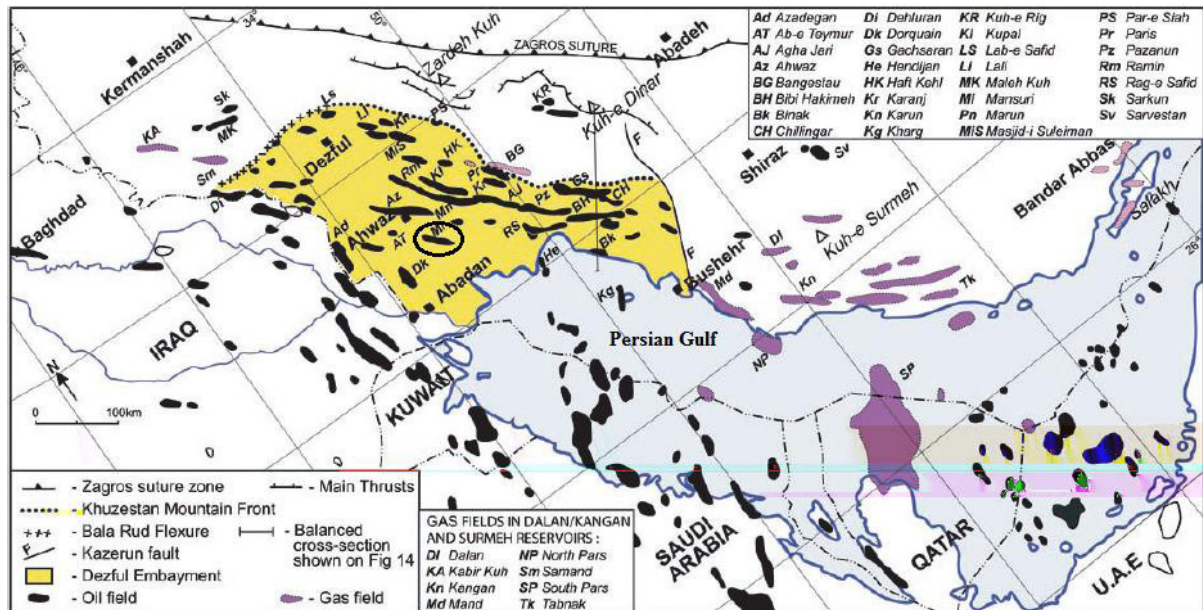


Figure 1. The Mansouri oilfield location map in the Zagros region (Bordenave & Hegre, 2005).

Stoneley waves are the type of sonic waves that are surface guided waveforms that propagate by "rolling" up the borehole wall. The Stoneley waveform has significant relevance in a number of applications although it can mask other waves due to its high amplitude. Other generated waveforms include borehole and surface guided waves typically formed by reverberation in the borehole. The Dipole sonic tools can fire the monopole transmitter at low frequency, specifically to generate Stoneley waves. These Stoneley waves can be used in fracture evaluation, for log quality control (LQC) dipole compression, and in shear waveforms studies. These waves exert pressure on the borehole wall and compress the formation fluids into porous media, creating a specific wave which is called Stoneley wave. In general, there are three types of waves including compression, shear and Stoneley, present in fast formations. However, only the compressional and Stoneley waves can be found in slow formations (Ellis and Singer, 2008).

In order to estimate permeability in slow formations, flexure waves are recorded by utilizing high technology logging tools that help finding permeability in slow formation reservoirs.

Dipole sonic tools use a directional source as well as directional receivers. The dipole source behaves like a piston, creating a

pressure increase on one side of the borehole and a decrease on the other. This causes the borehole to flex. This flexing of the formation directly excites compressional and shear waves in the formation. Propagation of this flexural wave is parallel with the borehole, whereas displacement is at right angles to the borehole axis and in line with the transmitter. The source operates at a variety of low frequencies, 4 to 8 kHz standard dipole, 2 to 4 kHz medium frequency dipole, and 0.25 to 1 kHz low frequency dipole. The frequencies are chosen to optimize the excitation of the flexural waves in specific formations. The lower frequencies give optimum results in large boreholes and in very slow formations. In addition, the depth of investigation can be increased (Ellis and Singer, 2008).

The compressional and shear waves radiate straight out into the formation. There is, however, an additional shear/flexural wave propagating up the borehole. It creates a piston type (dipole-type) pressure disturbance in the borehole fluid. In fact, this pressure disturbance can be detected by the directional receivers. The shear/flexural wave, initiated by the flexing action of the borehole, is dispersive. At low frequencies, it travels at the same speed as the shear wave, but at higher frequencies it travels at a slower speed.

Advanced technology dipole sonic tools such as DSI, WSTT and XMAC are to be

utilized in order to estimate the permeability in all formations, which is called continuous permeability. The XMAC tool was used in the present study. In a situation where core samples are not taken in drilling wells, the permeability may be computed from dipole sonic logging tools. Moreover, core permeability measurements are reported point-to-point while dipole sonic permeability is a continuous process.

Stoneley waves are dispersive (velocity varies with frequency) and are generated from the interaction between borehole and formation (Fig. 2). At low frequencies, it is called a tube-wave. A Stoneley waveform has a frequency content of 0.1 to 3 kHz, with the highest amount of energy in late arrivals at about 500 Hz. Stoneley waves are usually detected between 0 to 20 ms on the sonic waveform. In contrast, the shear wave forms are usually detected between 0 to 5 ms and are concentrated around 4 kHz (Close *et al.*, 2009).

Electrofacies analysis was carried out by thin sections, core analysis, and pressure capillary data (PC). The Electrofacies clustering of the Bangestan reservoir have been defined by all available data from 78 wells including GR, NPHI, RHOB, DT, SW and PHIE, which were simultaneously evaluated and interpreted.

Interpretation of well logs (Schlumberger, 1974) took a long time followed by applying the GEOLOG software with 91245 readings data and the self-organization map (SOM) technique (Vesanto, 1999). To study the electrofacies, 904 thin sections were prepared from those electrofacies intervals. In order to decrease uncertainty during investigation, thin sections from the borderlines of each electrofacies were not considered during analysis. All the specifications of lithology and texture were studied using an optical microscope. Coring sample operation was carried out at 7 wells including 1, 4, 14, 24, 44, 54 and 96. The core samples of 3 of these drilled wells (14, 25 & 44) were subjected to SCAL analysis.

Discussion

There are different factors that affect the Stoneley wave. Its slowness increases due to fluid movement in porous media as well as the mud cake around the borehole. The mud cake effect on slowness is usually a constant shift if the mud cake thickness is constant or of one type. Grain modulus is another major factor affecting the Stoneley wave slowness. If the lithology is changing from pure calcite to dolomite or to more siliciclastic, the effect on slowness will be varied. The pore fluid modulus is also affected. For instance, if the fluid is changing from liquid to gas, the

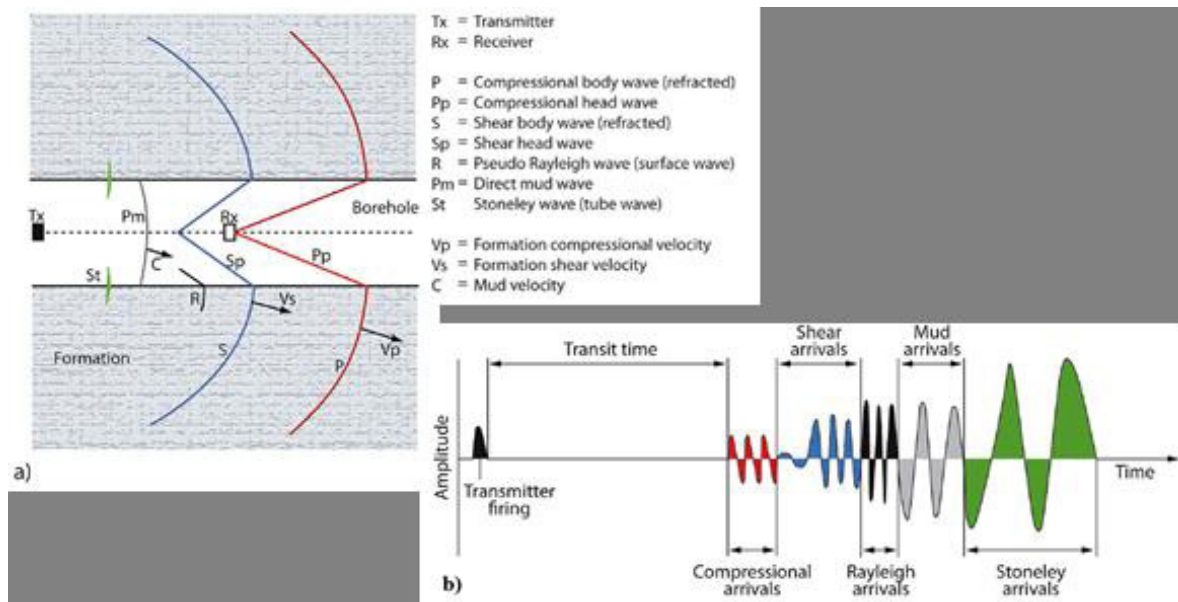


Figure 2. a) Important sonic waveform component propagation in a borehole as the P wave energy is detected; b) Schematic of the wave train detected at the receiver as a function of time (Close *et al.*, 2009).

predicted permeability increases exponentially. A Stoneley wave is affected by porous media fluid and by shear modulus at low frequency. Stoneley wave slowness can be modeled in non-permeable zones (AL-Adani and Barati, 2003; Winkler *et al.*, 1989) as follows:

$$DTST^2 = DTMF^2 + (DTSH^2 \times MFD)/RHOB$$

where

DTST = Stoneley wave slowness ($\mu\text{s}/\text{ft}$), DTSH = Shear wave slowness ($\mu\text{s}/\text{ft}$), DTMF = Mud filtrate slowness ($\mu\text{s}/\text{ft}$), MFD = Mud filtrate density ($\mu\text{s}/\text{ft}$), and RHOB = Density of the rock (g/cc).

By cross-plotting $DTST^2$ versus $DTSH^2/RHOB$ across a zero permeability zone, the slope of the straight line is MFD and the Y-intercept is $DTMF^2$ (AL-Adani and Barati, 2003). There must be one pattern on the linear fit plot: all data on the cross plot should be above or on the fitted line (Figure 3). This essential factor is observed in the present data.

The Stoneley permeability index is estimated by taking the ratio of actual measured Stoneley slowness and modeled slowness as per the above model. The formula can be written as follows:

$$KIST = DTST / \sqrt{[(DTSH^2 \times MFD/RHOB) + DTMF^2]}$$

This KIST model is still affected by variations in mud cake and formation fluid type. In addition, it does not provide a means to estimate mobility or permeability magnitude directly. Stoneley permeability index is not considered as the permeability estimation but it is an index of fluid movement in porous media around the borehole, since fluid movement is a function of pore throat distribution, pore shape, and pore size. Therefore the Stoneley permeability index is a tortuosity index only. These factors can be combined in a concept called Flow Zone Index (FZI). In fact, the Stoneley permeability index KIST is a direct measurement of FZI (Winkler *et al.*, 1989):

$$FZI \propto KIST$$

Since FZI approaches zero when the Stoneley permeability index approaches 1 in non-permeable zones and vice versa, and both of them approach infinity when permeability approaches infinity, then a simple relationship can be derived between FZI and STI, as follows (Wu and Yin, 2010):

$$FZI \propto (1 - KIST)$$

$$FZI = IMF (KIST - 1)$$

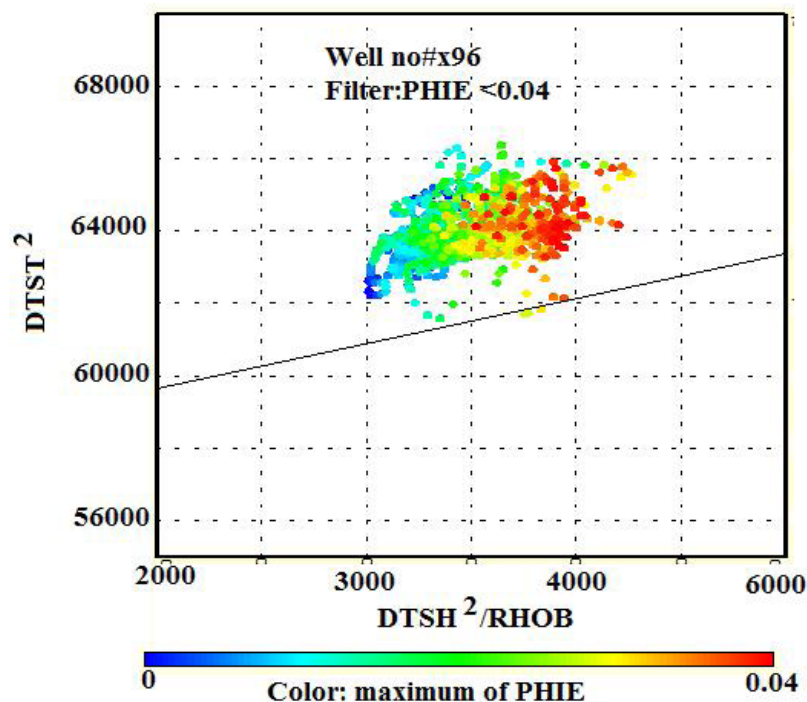


Figure 3. $DTST^2$ versus $DTSH^2/RHOB$ plot, the slope of the straight line is MFD and Y-intercept is $DTMF^2$

where:

FZI= Flow zone index

IMF= Flow zone index matching factor.

With this equation, the only empirical factor to match the actual permeability profile is IMF. Due to the effect of the grain modulus on Stoneley slowness, IMF can be computed in the probabilistic model by summing the volume weighted IMF for each individual mineral in the model:

$$IMF = \sum (IMFi.Vi).$$

The Stoneley permeability can be computed by using effective porosity and FZI according to the following equation (Amaefule *et al.*, 1993):

$$K = 1014. FZI^2. (\varphi^3 / (1 - \varphi)^2)$$

where:

K or KST: Permeability from Stoneley method (md)

φ = Effective porosity

FZI= Flow zone index.

To conduct this method and get the effective data, the following conditions should exist:

-Single phase fluid should exist in porous media.

-Temperature variation is negligible.

-Mud type cake should be single with fairly constant mud cake thickness.

-Sufficient logs should be available for volumetric lithology modeling.

In the present area under study, core data, MDT permeability or down hole production profile with constant draw down are available. However, in bad holes or severely rough surface conditions, this method is not valid.

Timur permeability

Permeability can be estimated in several ways one of the commonest of which is the Timur Equation (Timur, 1968):

$$K = 0.136 (\varphi^{4.4} / S_{w_{ir}}^2)$$

By applying this method, Timur permeability estimation can be compared with core and Stoneley permeability, which are identical (Figure 4). The measured permeability from core analysis and estimated permeability of Stoneley method are also showing the best match. In this figure, a relationship is observed among fluid saturation, water saturation, oil saturation, EF, PHIE and PHI-core, and Stoneley predicted permeability variation. As shown in the figure, EFs-1 and 2 containing higher oil saturation, and in other electrofacies, Sw values are high. Therefore, EFs-1 and 2 have the best quality in this reservoir.

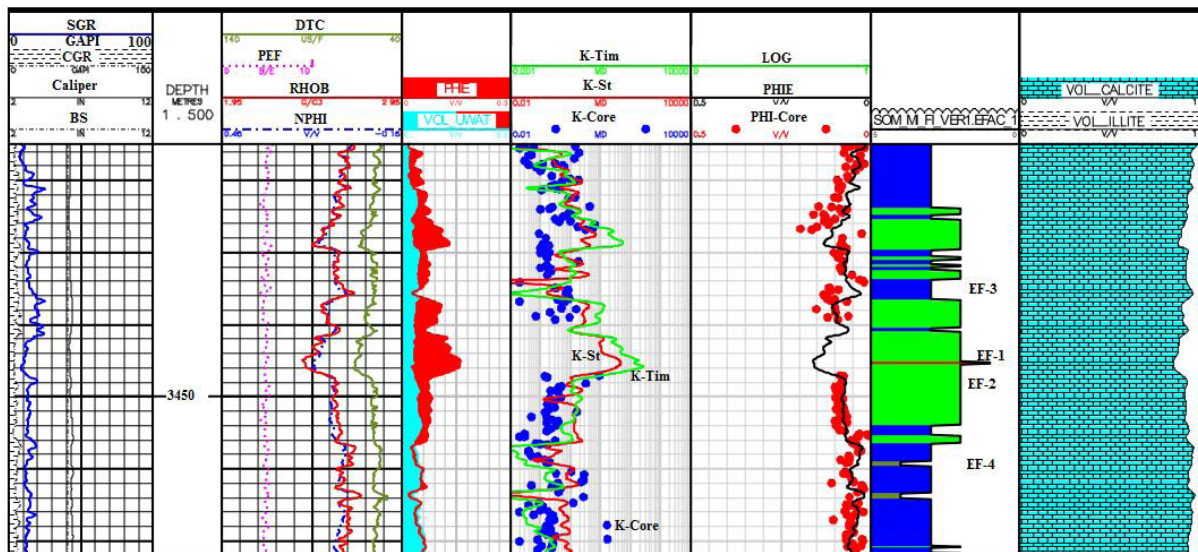


Figure 4. The comparison of permeability (K) data calculated from core analysis, Stoneley and Timur methods in one of the studied wells (Well#X96).

In order to differentiate reservoir zones from non-reservoir zones in the Bangestan field, all necessary data such as well logs, core samples, microscopic thin sections and geology software were used to determine electrofacies. All data were classified in 9 clusters by the SOM method. These rock types are plotted in the Bangestan reservoir in view of Sw vs PHIE (Figure 5). In general, capillary pressure (PC) is defined as the movement of fluids into pore throat and displacement of wetting fluids inside the pores (Jennings, 1987).

If the reservoir wetting fluid is constant, and supposing the size of pore remains the same, then capillary pressure will not change due to displacement of fluids. Therefore, by considering PC and water saturation data, it can be possible to combine some of the electrofacies together. According to the similarity of clusters and their combination, the 9 clusters were reduced to 4 clusters as the final clustering in the Bangestan reservoir of the Mansouri oilfield.

Electrofacies characterization

Petrophysical data average has been provided for each electrofacies (Table 1) as GR, DT, neutron porosity, density, PHIE and Sw

(Table-1). Statistical percentage of each electrofacies in this reservoir was plotted to present their frequencies (Figure 6A).

With respect to the electrofacies' depth and thickness, their distributions were analysed statistically. Comparison of electrofacies from a textural point of view clearly proved the fact that all electrofacies in the Bangestan reservoir consisted mainly of wackestone and packstone (Figure 6B). However, grainstone, dolostone and mudstone were also found in minor frequencies.

Drilling core analysis (Nelson, 2001) and Archie pore type classification (Archie, 1952) were applied to evaluate the reservoir quality. The study of core samples indicated that matrix porosity consisted of types I and III. The dominant porosity of EFs-1 and 2 is type B (visible by loop), EF-3 is type A (invisible porosity) and then followed by types B and D (vuggy and fracture porosity) in decreasing order. Most of the solution seems to have been found in EFs- 3 and 4. However, it is less frequent in EFs-1 and 2 (Figure 6C). This research has shown that vuggs are responsible for high reservoir quality in EFs-1 and 2 (Figure 7).

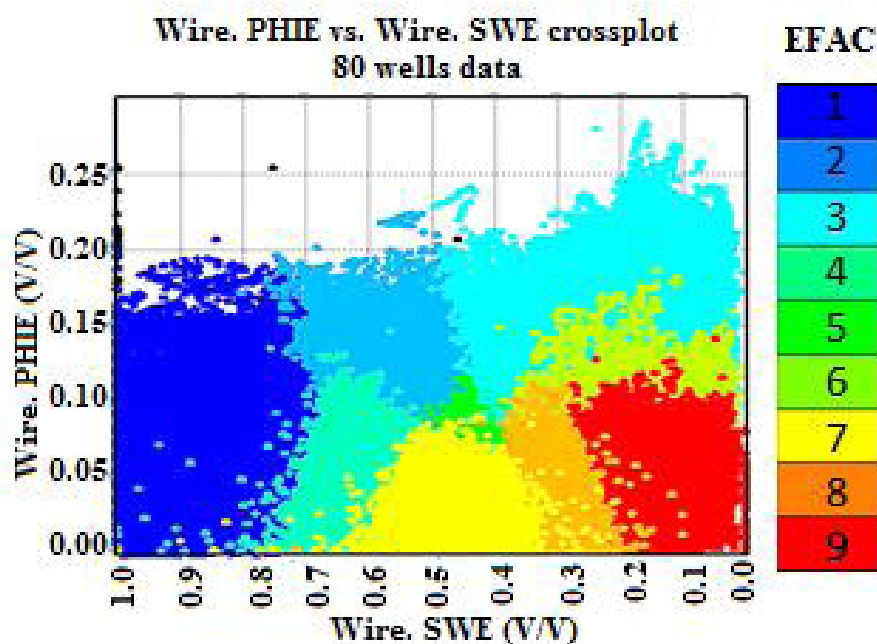
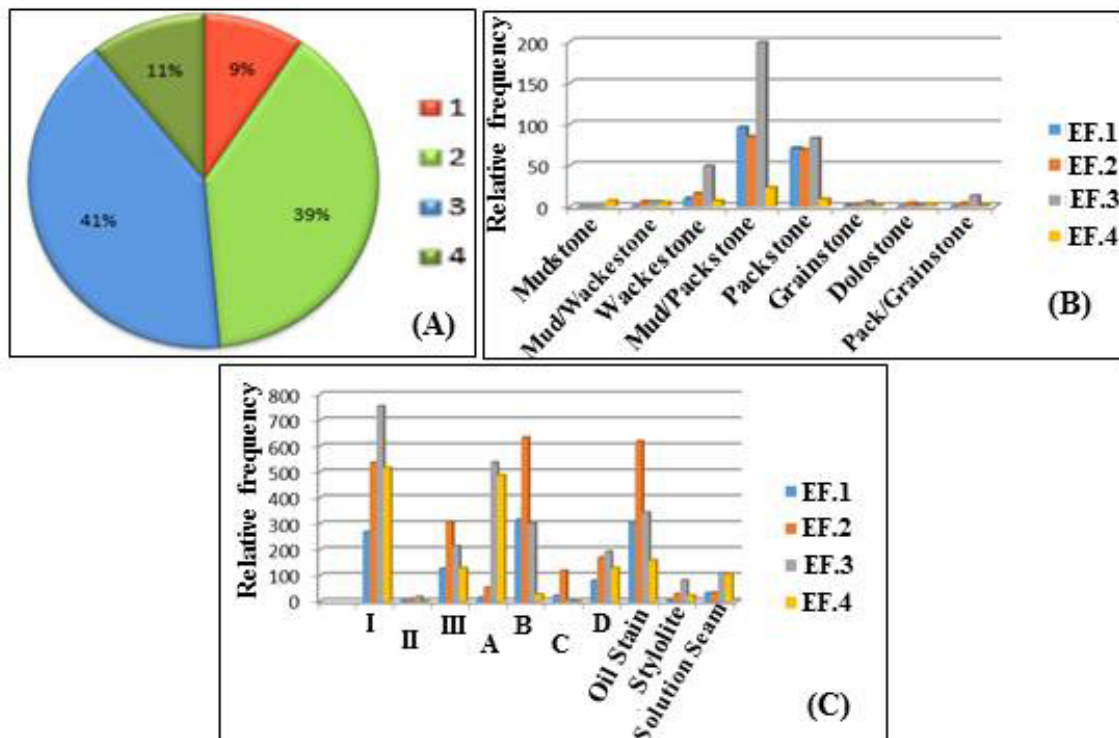
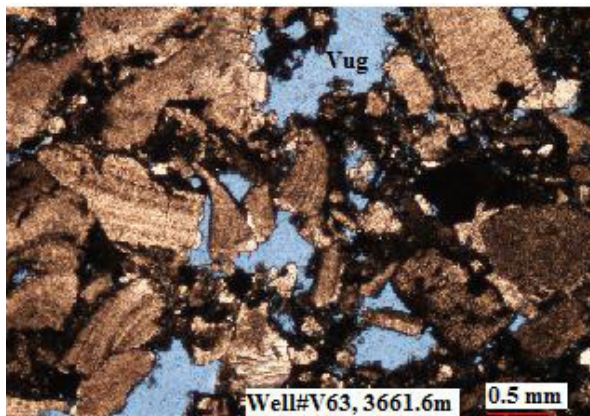


Figure 5. Presentation of the relation of nine EFs distribution in view of Sw and PHIE.

Table 1. The Petrophysical data average for four EFs in Bangestan Reservoir.

Electrofacies	GR °API	DT μs/f	Neutron porosity v/v	Density g/cc	PHIE v/v	Sw v/v
1	16.2	71	0.17	2.4	0.18	0.2
2	18.45	62	0.10	2.5	0.10	0.42
3	24.53	54	0.04	2.60	0.05	0.35
4	34.48	60	0.08	2.63	0.02	0.93

**Figure 6.** (A) The relative percentage of each electrofacies; B) Dunham textural variations and their distribution and C) The porosity type distribution based on Archie classification in all electrofacies of the Bangestan reservoir.**Figure 7.** The presence of vuggy porosity type is the main reason of high reservoir quality.

Electrofacies from well logs and Stoneley wave

EFs determined from Stoneley and well logs in Well # C150 were compared and presented a good correlation between them (Figure 8). However, differences are observed between these methods as well. The differences can be attributed to the higher resolution of EFs according to Stoneley wave rather than EFs by GEOLOG using well log data in some horizons (upper part).

As observed in this figure, EFs distribution is different from other plots related to heterogeneity and scarcity patterns in the reservoir. This issue can be controlled by lateral facies changes or diagenetic intensity such as dolomitization. Therefore, some caution should be exercised in field development programs.

Permeability variation compared to Electrofacies

To check the permeability data of core and Stoneley wave, the results of well # X96 (where core data and dipole sonic data were available), due to its special position, were compared and a harmonic and uniform pattern in variation was observed (Figure 4). Permeability estimated by the Timur method also indicated a reasonable match. The effective porosity also shows a direct relation with the permeability (Figures 9-11). The porosity changes are also showing the same impacts on all K-plots, Stoneley, core, and Timor. This has been verified in different wells.

The permeability predicted by the Stoneley and Timor methods and the core data were

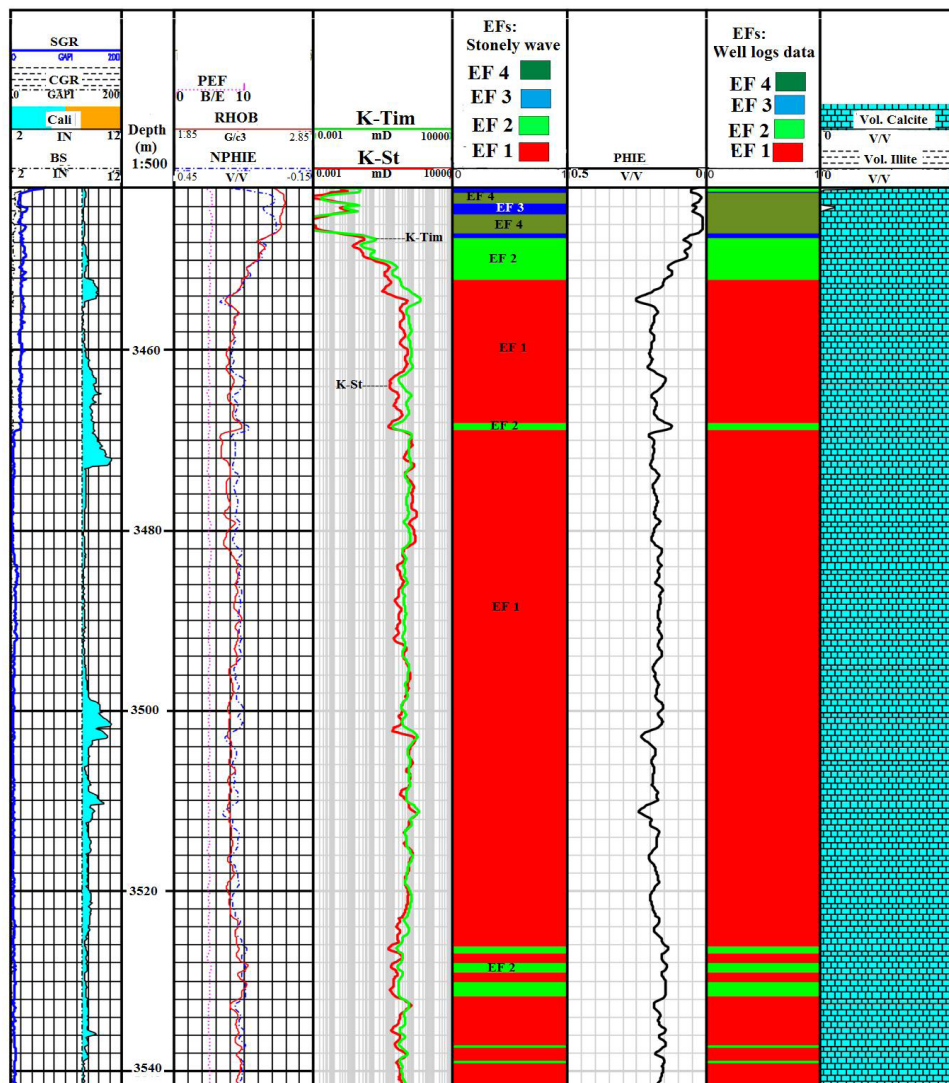


Figure 8. The comparison of EFs from Stoneley and EFs from well logs in Well# C150.

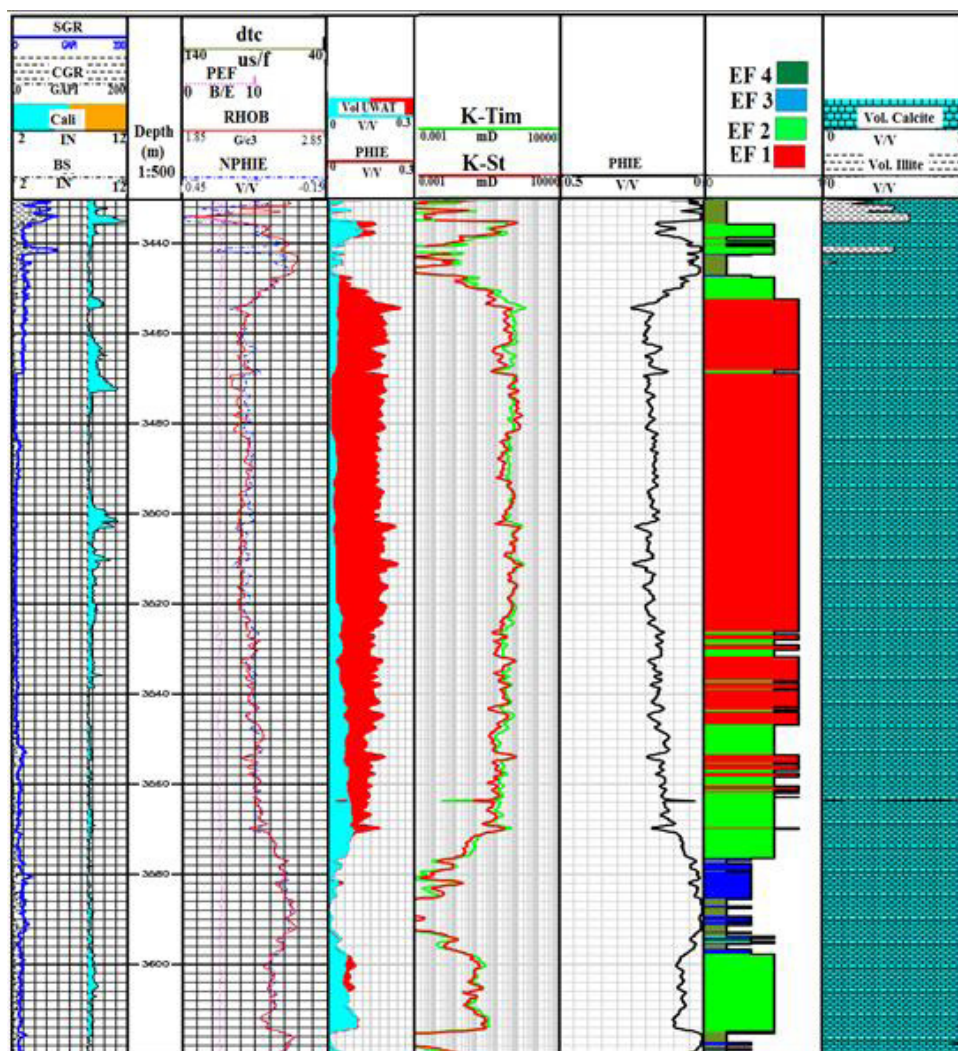


Figure 9. The comparison of K- ST and K- TIM permeabilities with EFs in Well#XY54.

also considered in all electrofacies. The study revealed that EFs 1, 2, and 3 can be classified as very good in quality but EF4 should be regarded as a non reservoir zone. The permeability predicted by Stoneley wave emphasized the same results. Therefore, those horizons or rock types with high permeability values by either core, Timor or Stoneley can be recognized immediately. Thus the Stoneley wave method can be used as an alternative tool to predict

the permeability of the horizons in the wells in which the core process is not successful or has not been run. This wave can also be employed to differentiate the rock type or electrofacies in high resolution and to evaluate the reservoirs (Figure 8). The ranges of predicted Stoneley permeability may be suggested to recognize the electrofacies in the Bangestan reservoir of Mansouri oilfield (Table 2).

Table 2. Detected electrofacies (EFs) and correlated to predicted Stoneley permeability.

EFs	Stoneley permeability relatively range (mD)
1	> 10
2	0.1-10
3	0.01-0.1
4	0-0.01

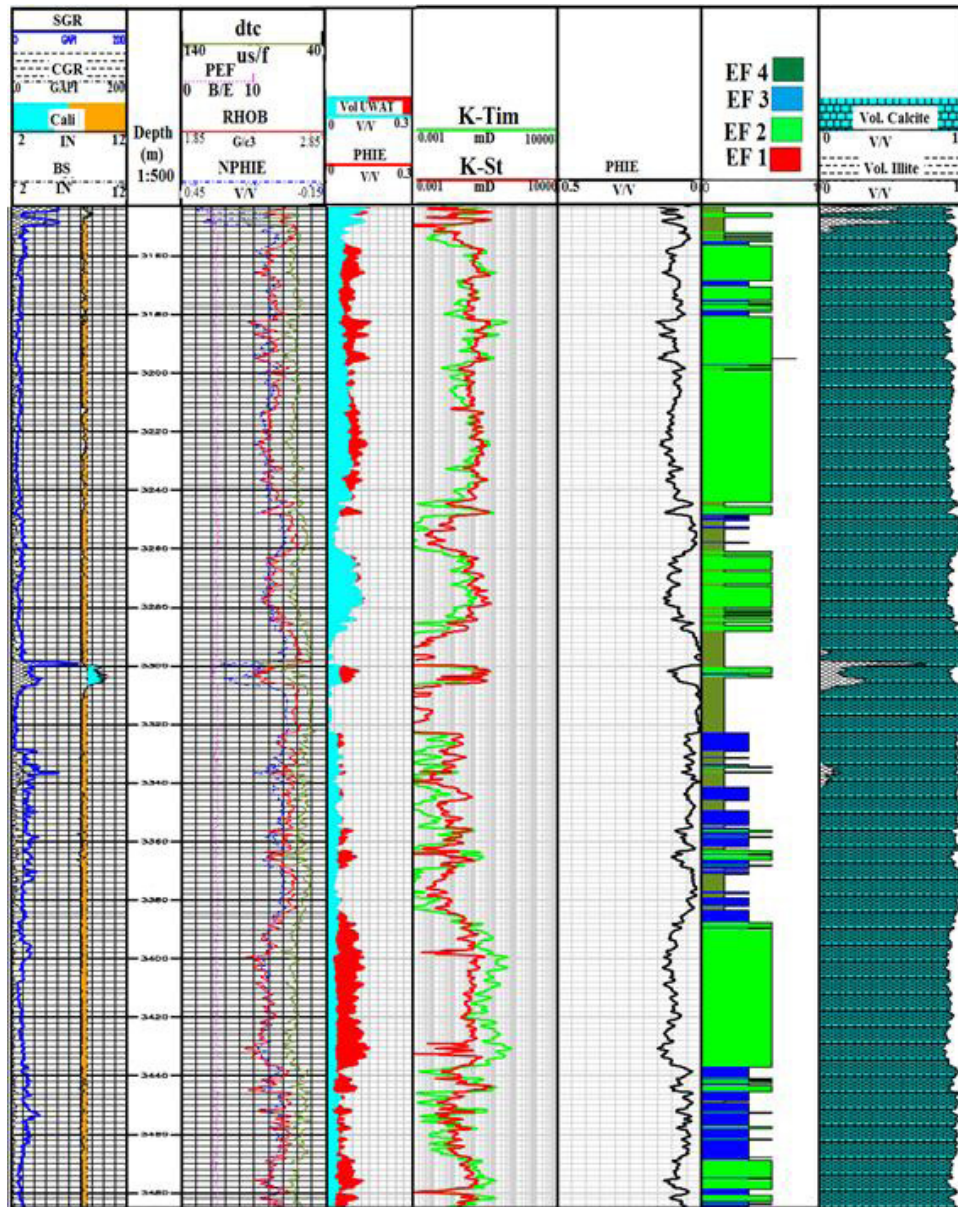


Figure 10. The comparison of K- ST and K- TIM permeabilities with EFs in Well#Z90.

Conclusions

Analysis and application of Stoneley waves as a unique way to predict reservoir permeability and its comparison with other provided electrofacies constitute the main goals of the present study. These were used to characterize the reservoir of Bangestan in the Mansouri oilfield, SW Iran. Comparison of the predicted Stoneley permeability logs with the core permeability indicated that they are in close match with each other. Due to the lack of core data in some wells, dipole sonic logs as an alternative tool can be substituted in order to estimate the permeability.

To find and separate heterogeneity of the reservoir in the Bangestan, electrofacies classification was used based on gamma ray, density, neutron, sonic, water saturation and PHIE data. A single model was given for the 78 wells studied. In this model, 4 electrofacies were summarized and recognized. EFs-1, 2 and 3 are showing very good to moderate reservoir quality and also with decreasing order. EF-4 was considered as a non-reservoir facies. The reason for high permeability in EFs-1 and 2 is attributed to the existence of abundances of vugs.

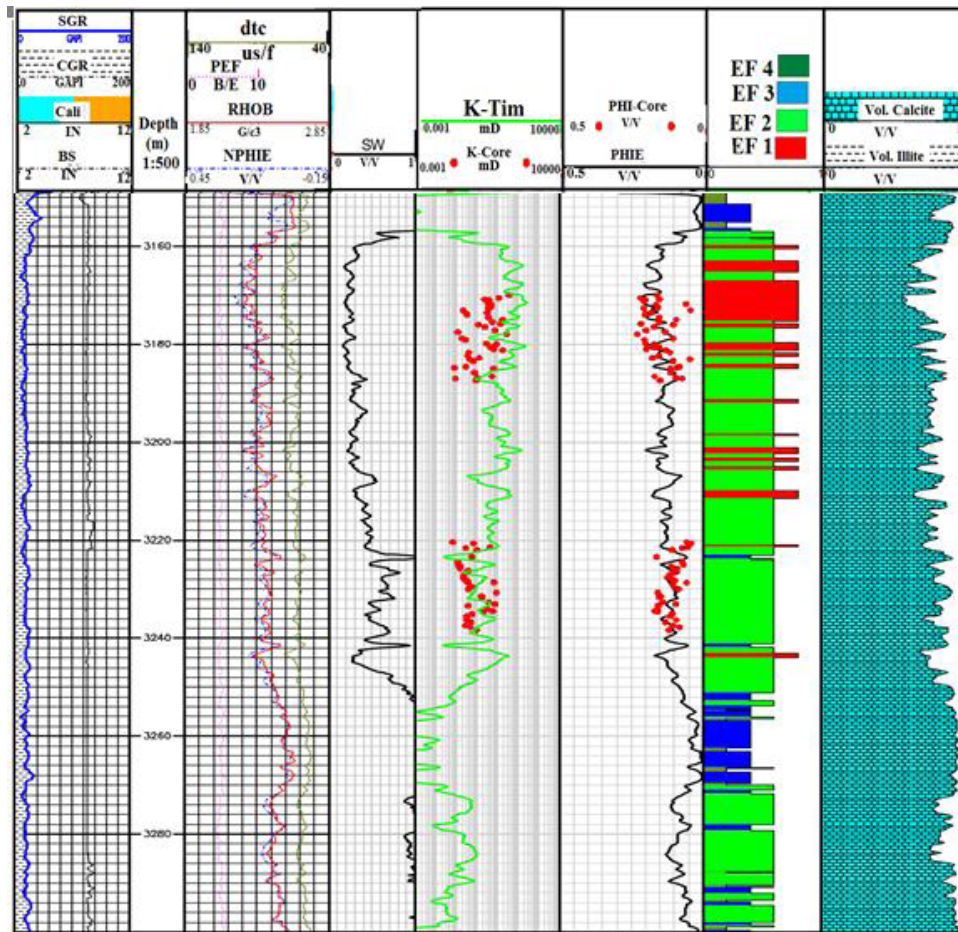


Figure 11. The comparison of K- TIM and K- core permeabilities with EFs in Well#W44.

All the studied intervals categorized in EFs-1 and 2 are indicating high permeability. Therefore, any future development wells drilled in those intervals containing EFs-1 and 2 will confirm high potential and production rates. EF-3 which contains less vugs is considered as the third order of reservoir quality after EFs-1 and 2. EF-4 should not be considered in view of permeability as having no reliable reservoir characteristics, so it will be defined as a non-reservoir zone. It can be concluded that the existence of vugs is the main reason for increasing the permeability and the reservoir quality.

Stoneley wave logs, the Timor method and core data correlated well in all electrofacies. It can be suggested that the Stoneley results represent a good candidate for core analysis and a reasonable method to differentiate electrofacies in the reservoirs specific to those horizons/wells where the coring process is not successful.

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Nomenclature defining symbols

DTST = Stoneley wave slowness ($\mu\text{s}/\text{ft}$),
 DTSH = Shear wave slowness ($\mu\text{s}/\text{ft}$),
 DTMF = Mud filtrate slowness ($\mu\text{s}/\text{ft}$),
 EF = electrofacies
 FZI = Flow zone index
 IMF = Flow zone index matching factor

K or KST= Permeability from stoneley method (md)
 ms = millisecond
 MFD= Mud filtrate density ($\mu\text{s}/\text{ft}$),
 RHOB= Density of the rock (gr/cc)
 φ = Effective porosity
 LQC= Log quality control

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